CHAPTER IV

ANALYSIS

During the two minutes and forty six seconds of totality four frames in the interferometer and six frames in the auxiliary experiment were exposed. As the grain size of the 35 mm film used in all these exposures is \( \sim 20 \, \mu \text{m} \) we can take \( 20 \, \mu \text{m} \times 20 \, \mu \text{m} \) as the pixel element. We then have more than \( 2 \times 10^7 \) pixels which have to be scanned and processed through a calibration curve to get relative intensities and hence line profiles.

In this chapter the tedious task of manual microdensitometry is described. Also discussed are the errors involved in the various measurements, the performance of the coelostat and the methods of determining coronal temperatures and relative Doppler shifts.

4.1 MICRODENSITOMETRY

4.1.1 The Microdensitometer:

Microdensitometry involves measurement of transmission \( (T) \) and hence photographic density \( D = -\log_{10}T \) at a large number of points (on the negative) separated from one another by distances of the same order as the grain size.
The microdensitometry of the eclipse negatives, which were sandwiched between two cleaned glass plates for protection, was carried out on a commercial Carl Zeiss densitometer, (Rapid photometer G 11). The densitometer essentially consists of a stable light source (in this case 12 V, 50 W) which sends a 3 mm diameter light beam through a small area of the film or plate to be scanned - before passing it through a magnifier and slit on to a gas filled photo cell. The slit defines the area of the film sampled by the detector. The resulting photo current which is a measure of transmission of the film can be amplified and recorded on a chart. The densitometer can be dynamically coupled to a chart recorder so that a one dimensional scan of the film could be automatically accomplished and the resulting transmission values recorded continuously on the chart. The densitometer has a special micrometer attachment which enables measurements to be made at 10 μm intervals. The lamp brightness can be maintained with a high degree of stability by the use of a magnetic voltage stabiliser [220 V/12 V 50 W]. A projection objective produces an enlarged image of the film field on a white screen in front of the main slit which enables the proper positioning of the film.
4.1.2 Initial adjustments:

The main slit width of the microdensitometer was optimally adjusted for a minimum value of 50 μm. The chart recorder was set at its maximum sensitivity level. A slow scanning rate of 0.02 revolutions of the drive shaft per minute corresponding to 30 μm per minute on the film was selected. The recorder chart speed was set at 20 mm/min.

The totality frames were separated and each mounted between two clean glass plates for microdensitometry. The 90 second exposure was the first frame to be selected for scanning. After focussing adjustments the X and Y motions in the instrument were used to locate the fringe centre by making the fringes tangential to the slit directions. The markings on the film edges were also brought to the slit centre and their positions read off. This procedure enabled scan directions to be specified properly. A short scan in the clear portion of the film was also taken to specify the 100% level.

4.1.3 Scanning:

The slow one dimensional scan was now taken through the fringe centre, in order to scan always
normal to the concentric fringes. At regular spatial intervals markings were impressed on the chart so that by interpolation, fringe centre could be located and inter-fringe distances found. The location of the fringe peaks with respect to the fringe centre also fixed their position in the solar corona. The location of each fringe in polar co-ordinates, i.e. in terms of the radial distance measured from the centre of the sun and the position angle measured from North point through East was then obtained graphically.

The film was now slightly rotated and the scanning process including reading of the fiducial marks at the film edges repeated to locate the new scan direction. This process was continued till the film had been adequately scanned. Depending upon the number of fringes present in a scan the scan time varied from 20 minutes to nearly an hour.

The same procedure was adopted for other interferometric frames. For the frames in the auxiliary experiment the procedure was essentially the same except that the scans were now taken radially outward from the well defined solar centre. Microdensitometric scans were also taken of the Mercury spectral line
calibration frame in order to determine the instrumental profile. Scans of the step wedges were also necessary to construct the photographic calibration curve.

Figure 4.1 shows a typical chart record of a scan. Since the interferometric scans were made radially not from the solar centre, but from the fringe centre, the fringes are not only located at different distances from the solar centre but also have a spread in position angle. The decreasing interfringe distance with increasing distance from the fringe centre can be readily seen.

The transmittance curves of the type shown in Figure 4.1 obtained for all the scans were subsequently digitised in a special instrument by reading the chart at 0.5 mm intervals. The digitised values were stored in magnetic tapes and were subsequently used to generate line profiles.

4.2 CHARACTERISTIC CURVE

After obtaining photographic densities \( D = -\log_{10} T \) the next step in the analysis is the construction of photographic characteristic curve which will permit
Fig. 4.1: A typical chart record of a Microdensitometric scan.
their ready conversion into the physically more meaningful relative intensities.

The step wedge calibration available at the beginning of the films in both the experiments was made use of for this purpose. The step wedges were scanned by the microdensitometer and the photographic densities so obtained were plotted against the diffuse densities or $\log_{10}E$ values supplied by the manufacturer.

The resulting curve is shown in Figure 4.2. The relative intensity corresponding to the given photographic density could now be read off from the graph. A digitised version of the curve with suitable interpolation serves the same purpose for the photographic density values stored in magnetic tapes.

The separation between the peaks of two adjacent fringes could be readily read off on the chart. As this separation also corresponds to one free spectral range (F.S.R.), we could assign for each point in a profile a wavelength value measured from the line centre or fringe maxima.
Fig. 4.2: The photographic characteristic curve.
4.2.1 Reciprocity failure:

Unlike astronomical films like 103 a-F the film used at the eclipse - Tri X is unfortunately subject to effects of reciprocity failure. Reciprocity failure essentially means the break down of the reciprocity law between illumination and exposure time due to multistage processes by which a single grain is blackened. Doubling the exposure time and halving the intensity are not equivalent. The effective speed of the film decreases for longer exposures and so the contrast factor $\gamma$ of the film changes. The effects of reciprocity failure on the measurements of coronal temperatures were studied by considering relative intensities in the same spatial segment in two different interferogram frames. The values of temperature obtained from the 90 second frame and those from the 30 and 10 second frames extrapolated to a 90 second equivalent frame by appropriate additions

i.e. $\log_{10} E_{30} + \log_{10} 3$ for the 30 sec. frame and

$\log_{10} E_{10} + \log_{10} 9$ for the 10 sec. frame

gave results with a dispersion of $< 10\%$. Since the densitometric measurement errors themselves are of
this order it was concluded that reciprocity failure does not affect the evaluation of coronal temperature within experimental limits.

4.3 **INSTRUMENTAL PROFILE**

The instrumental line shape was derived from the mercury calibration line ($\lambda$ 5460.74 Å) profiles recorded on the film soon after totality. As the typical width of the calibration line is $\sim 6$ mÅ (Chabkal, 1953) the broadening of the calibration line observed was entirely caused by the instrument. The profile was determined in a manner similar to that for eclipse fringes through microdensitometry and the calibration curve. Figure 4.3 shows the instrumental profile along-with the theoretical Airy and Gaussian profiles of the same half width. It is seen that the instrumental line shape closely follows the Airy profile. Further the half width (FWHM) of 0.23 Å is exactly what is expected theoretically for this etalon as specified in Table 2.3. The result indicates that the etalon had been in excellent alignment throughout the period of totality.

The microdensitometer slit width of 50 $\mu$m (d) introduces a rectangular scanning function of the same
Fig. 4.3: Instrumental profile of the Fabry-Perot Interferometer.
width which has to be convolved with the etalon function (B). The etalon function can be approximated by an Airy function (A) of spectral width 0.23 Å which in the plane of the slit corresponds to 200 μm (a). This type of convolution has been considered in detail by Chabbal (1958). The convolution due to the small value of the ratio d/μ in our case does not appreciably affect the instrumental profile. Hence the effect of scanning function can be safely excluded from the analysis.

4.4 DETERMINATION OF CORONAL TEMPERATURES FROM THE DATA

In order to obtain the true line profiles and hence temperatures, it is necessary to correct for the broadening caused by the instrument. A general approach to the problem is one of detailed deconvolution involving Fourier methods, which only needs to be adopted when the true line width is not large compared to the instrumental width. In the present case the instrumental width of 0.23 Å is small enough compared to the true line widths (0.7 – 1.0 Å) to justify the use of a simpler approach of Gaussian approximation for both line and instrumental profiles (method I). However, after the 'first look' results had been obtained
using this approximation, the detailed deconvolution involving no prior assumptions about coronal and instrumental line shape was carried out with similar results. (Method II).

4.4:1 Method I:

The first method is a simple one which assumes that the coronal profiles are Doppler broadened Gaussian profiles. The continuum contribution ($E_c$) to the line is taken to be the mean of the continuum level on either side of a fringe peak in the interferogram. The half intensity points, in the presence of the continuum will have a value $E_p - E_c + E_c = \frac{E_p + E_c}{2}$ where $E_p$ refers to the peak intensity value. The separation ($X$) between photographic density points on the chart, on either side of the fringe peak, corresponding to this half intensity can then be determined. If $X_0$ is the mean distance from this fringe peak to the adjacent peaks on the chart, then the full width at half maximum of the line is given by

$$\Delta \lambda_D = \frac{X}{X_0} \cdot 4.69 \text{ Å}$$

The width is still uncorrected for instrumental broadening. Assuming a Gaussian instrumental line shape of
width 0.23 Å we get the corrected Doppler width \( \Delta \lambda_c \) given by

\[
\Delta \lambda_c = \left[ \Delta \lambda_D^2 - 0.23^2 \right]^\frac{1}{2}
\]

The Doppler temperature \( T_D \) readily follows from the expression

\[
\Delta \frac{\lambda_c}{\lambda_o} = 7.16 \times 10^{-7} \sqrt{\frac{T_D}{m}}
\]

where \( m \) is the mass number of the element giving rise to the line. In our case \( m = 56 \) and \( \lambda_o = 5302.86 \text{ Å} \).

The Doppler width of the line (typically \( \Delta \lambda_c \sim 0.8 \text{ Å} \)) greatly exceeds the instrumental width (0.23 Å) so that the corrected width (\( \Delta \lambda_c \)) does not differ from the observed width by more than a few percent. The temperature obtained by this method therefore does not differ appreciably from the more elaborate method to be described below. The Gaussian line shape assumed for the eclipse profiles also appears to be valid except in certain regions in the corona where there are clear indications of line splitting. These interesting regions will be dealt with in the chapter on results.
4.4.2 Method II:

This elaborate and general method of obtaining line profiles has been applied to the digitised data stored in magnetic tapes. This method does not assume a priori, any line shape either for the coronal line or for the instrumental broadening. A computer program has been devised and applied to the data. The various steps in the program are listed below:

1. Determination of photographic densities from digitised transmittance values.

2. Determination of relative intensities (E) by interpolation, in the digitised photographic characteristic curve. Correction for the continuum (E_c) is also performed at this stage.

3. Location of fringe peaks and assignment of the wavelength values measured from the peak for all points in the line profile.

4. Deconvolution process. The Mercury calibration profile is first interpolated to get relative intensity values for the same \( \Delta \lambda \) as the eclipse profile. The two profiles are then independently normalised. Digital
Fourier transforms of the two normalised profiles are taken followed by point by point division of the Fourier transform of the eclipse profile by that of the mercury profile i.e. in the Fourier domain deconvolution is reduced to a simple division. An inverse digital Fourier transform is then performed to retrieve the coronal profile freed from instrumental effects, completing thereby the process of deconvolution.

5. Least square analysis of the deconvolved line profile. A linear least square fit has been made between logarithm of intensity \( \ln E \) and \( (\Delta \lambda)^2 \). For a pure Gaussian profile

\[
\ln E = \ln E_0 - 4 \ln 2 \left( \frac{\Delta \lambda}{\Delta \lambda_D} \right)^2
\]

where \( \Delta \lambda_D \) is the required width (FWHM) of the profile and \( E_0 \) the peak fringe intensity. A pure Gaussian profile will yield a perfect straight line fit. Departures from linearity are a measure of the departures of the profile from Gaussian. From the slope of the least square straight line, line width \( \Delta \lambda_D \) can be calculated and hence the Doppler temperature \( T_D \) can be determined.
The program has also the provision for calculating temperature gradients and turbulent velocities which cause excess non-thermal broadening. The results obtained from this program are discussed in Chapter V.

4.5 **DETERMINATION OF DISPERSION (RELATIVE LINE OF SIGHT DOPPLER VELOCITIES)**

The location of a fringe peak relative to the fringe centre in an interferogram carries information about the line of sight Doppler velocities. In the microdensitometry of the eclipse frames, fringe peaks could be located absolutely to within \( \pm 0.05 \) mm on the film as measured from the fringe centre. The interfringe distances could however be determined with a much greater accuracy - \( \lesssim \pm 0.005 \) mm. This accuracy limit translates to a relative line of sight velocity of \( \pm 6 \) km sec\(^{-1}\). Any shift between the centres of the fringe patterns in the eclipse frames and the calibration frames can significantly affect absolute Doppler velocity determination. Since the relative fringe peak positions can be much better determined (\( \lesssim \pm 0.005 \) mm) than the absolute positions with respect to the fringe centre (\( \pm 0.05 \) mm) we have considered in the analysis only relative Doppler shifts and their standard deviation.
for each scan. An examination of 659 fringes spread over 59 scans made radially outward from the fringe centre in 90 and 30 second frames has resulted in 59 velocity dispersion values which should be accurate to ± 6 km sec\(^{-1}\).

In order to verify this accuracy limit, the calibration frame was rescanned treating it as a hypothetical eclipse frame in \(\lambda 5461 \, \AA\). The dispersion value of 7 km sec\(^{-1}\) obtained agrees well with the calculated error and justifies the method for detecting relative Doppler shifts greater than 7 km sec\(^{-1}\). Since each scan is made radially outward from the fringe centre, which is kept displaced from the solar centre, the dispersion velocity is necessarily averaged over a few degrees of position angle and also over the entire radial extent of the scan. The reduction, thus does not permit conclusions regarding radial variation of the dispersion velocity.

The Fabry-Perot spacer value (\(\mu t\)) required in the calculation of Doppler shifts was experimentally determined after a careful study of the calibration frame. For this purpose a special projection technique by which the frame could be magnified by a factor of \(\sim 200\) was developed and used. Measurements on the calibration frame yielded a spacer value of 307 \(\mu\)m with an estimated error of \(< 1\%\).
Consider the basic Fabry-Perot relation neglecting phase effects on reflection. We have

\[ 2 \mu t \cos \Theta = n\lambda \]  \hspace{1cm} (2.5)

The rest wavelength of the green line has been taken as \( \lambda_0 = 5302.86 \, \text{Å} \) (Unsold, 1977) which will peak at an angular position \( \Theta_0 \) given by

\[ 2 \mu t \cos \Theta_0 = n \lambda_0 \]

\[ \therefore \quad \frac{\cos \Theta - \cos \Theta_0}{\cos \Theta_0} = \frac{\lambda - \lambda_0}{\lambda_0} = \frac{v}{c} \]

Measuring the radius (R) of the fringe and using the value (F) of the focal length of the camera lens we get \( \Theta = \tan^{-1} \left( \frac{R}{F} \right) \). \( \Theta_0 \) for the same order can be found directly from the basic equation as \( \mu t \) is known. Hence the line of sight Doppler velocity (V) can be calculated. The standard deviation in V in each radial scan which is more accurately determined is the value actually used in drawing the conclusions discussed in the next chapter.
4.6 MICRODENSITOMETRIC ERRORS

In determining the accuracy with which one can measure the coronal temperature it is important to consider the effects of grain noise of the film. It was found that the most sensitive parameter in the determination of line widths is the position of fringe maximum or the position of maximum photographic density. By changing this position by an amount corresponding to grain noise one could evaluate the variations in line widths and hence the temperature. It was found that for fringes with good contrast, the temperatures were accurate to within 10-15% of the stated value. For fringes in the outer portions of the emission corona, which had a lower contrast, the temperature measurements were less accurate (\( \frac{S_T}{I} \times 100 \sim 25 \)). The results discussed in the thesis are derived only from those fringes which show a good contrast and whose temperatures have an error not exceeding 15 percent of the stated value.

4.7 SPATIAL RESOLUTION

The grain size of 20 \( \mu \)m corresponds to less than 3" in the sky. However as a Fabry-Perot etalon
is used, the achievable spatial resolution in the scan direction is decided by the spacing between the fringes. The etalon centre being displaced with respect to the solar centre in the camera frame, results in the spacing between the fringes being variable at different points in the corona. Typically the mean separation between the fringes is 0.2 mm on the film which corresponds to 26" in the sky. In terms of solar radius this resolution equals $0.028 R_\odot$. Each fringe is built up by light received not from a point but from a small finite portion of the corona. Each fringe occupies a spectral region of approximately $1/5 \times$ F.S.R. The region of the corona over which each fringe is averaged is $\sim 0.04$ mm on the film or $\sim 5"$ in the sky or $\sim 0.005 R_\odot$ in terms of solar radius.

4.8 TRACKING ERRORS

A serious limitations to the spatial resolution occurred due to the under-performance of the coelostat. Due to the inaccurate tracking there was a slight drift of the coronal image on the film. This error was quantitatively evaluated by considering the separation of the fringe centre and solar centre in all the exposures.
Table 4.1 lists this separation averaged over all the scans of each exposure along with times (IST) corresponding to the mid point of each exposure.

Table 4.1
Fringe Centre Solar centre separation

<table>
<thead>
<tr>
<th>Exposure</th>
<th>Mean separation (mm)</th>
<th>Mid Exposure time (IST)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>4.97</td>
<td>15h 41m 10s</td>
</tr>
<tr>
<td>90</td>
<td>4.67</td>
<td>15h 42m 08s</td>
</tr>
<tr>
<td>30</td>
<td>4.08</td>
<td>15h 43m 20s</td>
</tr>
</tbody>
</table>

In case of perfect tracking the separation would be constant for all the exposures. The systematic reduction in the separation when the exposures are listed chronologically indicates the drift. The net drift is 0.89 mm in 130 seconds. This corresponds to 0.12 R° or 1.94' in the sky. The drift rate appears to have been constant. Table 4.2 lists the limiting spatial resolution for the different exposures.
Table 4.2
Tracking Error - Achievable spatial resolution

<table>
<thead>
<tr>
<th>Exposure</th>
<th>Spatial Resolution achievable in ( R_\odot ) units</th>
<th>Spatial Resolution achievable in arc seconds</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.009 ( R_\odot )</td>
<td>8'7</td>
</tr>
<tr>
<td>30</td>
<td>0.028 ( R_\odot )</td>
<td>26&quot;</td>
</tr>
<tr>
<td>90</td>
<td>0.84 ( R_\odot )</td>
<td>1'18'3 (=78'3)</td>
</tr>
</tbody>
</table>

4.9 **AUXILIARY EXPERIMENT - SPATIAL RESOLUTION AND SENSITIVITY**

The tracking of the Celestron-8 telescope used in the auxiliary experiment was far superior to that of the coelostat. Further since this experiment involved only photography of the corona in the green line, the spatial resolution achievable was essentially determined by the grain size of the emulsion or was seeing limited. For this 20 cm diameter f/10 optical system, 20 \( \mu \) m grain size corresponds to \( \sim 2" \) in the sky. The resolution is hence mainly seeing limited.

The intensity (E) measurements in this case fall mainly in the linear region of the characteristic curve.
and would be accurate to within 5% of the quoted value. Plots of \( \log_{10} E \) vs \( R/\sigma^2 \) and \( \log_{10} E \) vs \( R \) have been made for 24 position angles of a frame exposed for 15 seconds. A linear least square analysis has also been carried out to determine the scale height temperatures which are average values for an entire scan. Significant departures from linearity occur along many position angles indicating that the temperature cannot be considered uniform over the entire scan region. A spatial wave pattern observed in a particular scan (at position angle 316°) and its scientific import are discussed in the next chapter on results.